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PARAMETERS AND CHARACTERISTICS OF ELEMENTS OF AUTOMATION

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INTERNATIONAL FEDERATION OF AUTOMATIC

CONTROL (IFAC)

Scientific and Engineering Committee on Components

A System of Characteristics and Parameters is Proposed for Evaluating the Elements of Automation.

PART I. BASIC CHARACTERISTICS AND PARAMETERS OF ELEMENTS ASSOCIATED WITH AN ANALOG CONVERTER

Section 1. Static Parameters and Characteristics

Sensors, amplifiers and other components which establish a continuous /3* functional association of two circuits (input and output) are determined by the following series of relationships and parameters.

1. The most important one of these relationships is the control characteristic $y = f(x)$, which establishes the variation of the output parameter y as a function of the input parameter x (fig. 1). When hysteresis is present in the mechanical or magnetic part of the sensor, the forward and return branches do not coincide.

2. The control characteristic is limited by the lower and upper limits of the input x_{min} and x_{max} and output y_{min} and y_{max} parameters. Each of these parameters is associated with a definite input power $P_{x\ min}$ and $P_{x\ max}$ and output power $P_{y\ min}$ and $P_{y\ max}$.

3. In addition to the upper limiting value x_{max}, which is determined by the extreme operating point on the control characteristic, there is a quantity $x_{max\ lim}$, which is the maximum permissible value from the standpoint of the

*Numbers given in the margin indicate the pagination in the original foreign text.

thermal, mechanical or electrical strength of the sensor input parameter x. The quantity $x_{max\ lim}$ (or the corresponding value of power $P_{x\ max\ lim}$) is sometimes referred to as the overload capacity of the sensor.

When $x_{max\ lim}$ acts for a period of time T_{lim} (or the equivalent, energy $A_{lim} = P_{x\ max\ lim}\ T_{lim}$, the sensor must not change its properties and characteristics.

4. The ratio $y/x = S$ is called the sensitivity ("total sensitivity"). /4 More frequently the value $\Delta y/\Delta x = S'$ is used, which is the differential (or local) sensitivity. S and S' are constant only when the components have ideal linear characteristics. If the characteristics are nonlinear, then $S = f_a(x)$ and $S' = f'_g(x)$.

5. We can differentiate between components without variations in the tuning $(x_{max}-x_{min})$ = const and $(y_{max}-y_{min})$ = const and x_{max} = const and elements with variable tuning. Components with variable tuning may be achieved in the following manner

(a) by varying the values of x_{max} when $(x_{max}-x_{min})$ = const and $(y_{max}-y_{min})$ = const;

(b) by varying x_{max} and $(x_{max}-x_{min})$ when $(y_{max}-y_{min})$ = const;

(c) by varying $(y_{max}-y_{min})$ when x_{max} = const and $(x_{max}-x_{min})$ = const;

(d) by varying x_{max}, $(x_{max}-x_{min})$ and $(y_{max}-y_{min})$.

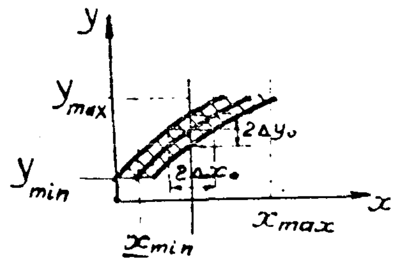

Figure 1. Variation in value of output parameter as function of input parameter.

The possible values of x_{max}, $(x_{max}-x_{min})$, $(y_{max}-y_{min})$ are shown by means of a table of control characteristic.

6. In a series of cases components with continuous transformation are used which have several inputs (for example, two or three) and consequently several input signals. In this case the control characteristic $y = f(x_1, x_2, x_3 \ldots)$ is constructed as a function of one of the input signals, while the values of the other signals are used as variable parameters when the curves are constructed (fig. 2).

7. In the general case the variation of output parameter y (for example, current or gas or liquid consumption) is determined as

$$y^{\alpha} = \frac{v}{R_x} \text{ or } y = K_x \cdot v^{1/\alpha},$$

where v is a quantity which in a given energy scheme is the source for the origin of quantity y;

R_x is the quantity which depends on the physical or structural factors and which may be determined as the "resistance";

$K_x = I/R_x^{1/2}$ is a quantity which can be called the "specific admittance."

In actual elements the parameter x causes a variation in R_x (or K_x), i.e.,

$$R_x = F(x) \text{ or } K_x = F_1(x),$$

this leads to a relationship $y = K_x \cdot v^{1/2}$ and to a control characteristic $y = v^{1/2} \cdot F_1(x) = f(x)$.

Therefore in many cases it is expedient to represent the elements given by $R_x = F(x)$ or $K_x = F_1(x)$, by the corresponding relationship $y = f(x)$ when $v = 1$.

When the load is connected in series and has a resistance R_L we have $v_0 = v_L + v$

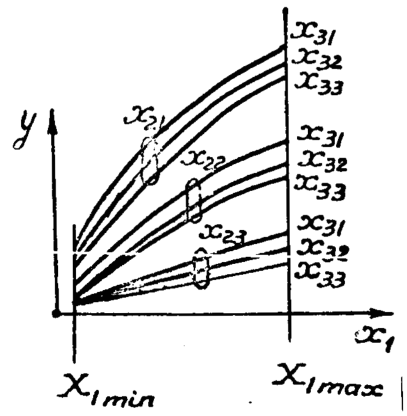

Figure 2. Functional characteristic.

or $v_0 = y^{\alpha} R_L + y^{\alpha}/K_x^{\alpha} = y^{\alpha}\,[R_L + 1/K_x^{\alpha}]$

and consequently

$$y = \frac{v_0^{1/\alpha}}{[R_L + \frac{1}{K_x^{\alpha}}]^{1/\alpha}} = \frac{v_0^{1/\alpha}\cdot K_x}{[R_L \cdot K_x^{\alpha} + 1]^{1/\alpha}} .$$

Examples

As an example we consider the control valve in the flow of a working liquid. In this case the output parameter is $y = Q$

$$\xi_x \frac{\rho Q^2}{2g} = \Delta P \quad \text{or} \quad Q = \left[\frac{2g}{\rho\,\xi_x}\right]^{\frac{1}{2}} \Delta P^{\frac{1}{2}} = K_x \cdot \Delta P^{\frac{1}{2}} ;$$

where ΔP is the pressure difference; /6

Q is the liquid consumption, m^3/cm^2 sec;

ρ is the specific weight of the operating liquid, tons/m^3;

g is the acceleration due to gravity;

ξ_x is the hydraulic resistance factor which is a function of the input parameter x, and also of the physical properties of the liquid and the design of the valve.

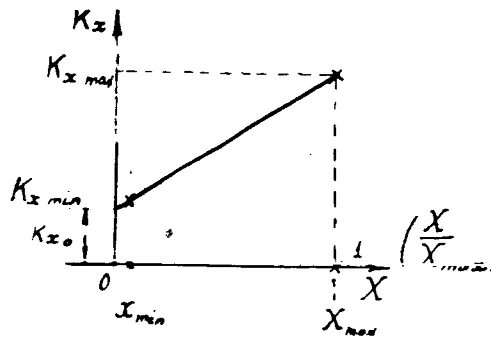

Figure 3. Variation $K_x = f(x)$.

In the case of the valve, the input parameter is the displacement of the valve rod $x = H$. Figure 3 shows the function

$$K_x = F\left(\frac{x}{x_{max}}\right) = F\left(\frac{H}{H_{max}}\right).$$

The following functions are most commonly used

(a) $K_x = K_{x0} \cdot e^{h_1\left(\frac{H_x}{H_{100}}\right)}$ - logarithmic characteristics;

(b) $K_x = K_{x0} + h_2\left(\frac{H_x}{H_{100}}\right)$ - linear characteristic.

The value $H = 0$ corresponds to $K_{x\ min}$ and y_{min}, while the value $H = H_{100}$ corresponds to the values $K_{x\ max}$ and y_{max}.

In the case of the valve the relationships $K_x = F\ (H_x/H_{100})$; H_{100}; $K_{x\ min}$ and $K_{x\ max}$ are usually assigned (to determine y_{min} and y_{max}); $K_{x\ max}/K_{x\ min}$.

8. The operation of the sensors is frequently associated with a continuous removal of energy from the input circuit. In this case it is necessary to know the input impedance, which may be determined in terms of the apparent consumed power N_K as /7

$$\bar{Z}_{in\,r} = \frac{N_K}{I^2}; \quad \bar{Z}_{in\,\theta} = \frac{\Delta\theta^\circ}{\Phi_\theta};$$

$$\bar{Z}_{in\,m} = \frac{\bar{P}_m}{\bar{V}_m} \qquad \text{etc.}$$

To achieve a correct selection of the parameters of the control (output) circuit, it is also necessary to know the output impedance of the sensor Z_{out}.

9. Under actual conditions in addition to the effect of the parameter x, the sensor is also subject to various external factors: the temperature θ^{o}, pressure p and humidity Z% of the surrounding medium, mechanical acceleration a and vibration A_F. It is also possible to have a variation in the position of the element in space, i.e., of the angle α. Thus we have the following expression for the variation in the output parameter

$$y = f(x, \theta^{\circ}, p, Z\%, a, A_F, \alpha)$$

or

$$\Delta y = \frac{dy}{dx}\Delta x + \frac{dy}{d\theta^{\circ}}\Delta\theta^{\circ} + \frac{dy}{dp}\Delta p + \cdots + \frac{dy}{d\alpha}\Delta\alpha$$
$$= \frac{dy}{dx}\left[\Delta x + \frac{\frac{dy}{d\theta^{\circ}}\Delta\theta + \frac{dy}{dp}\Delta p + \cdots + \frac{dy}{d\alpha}\cdot\Delta\alpha}{\frac{dy}{dx}}\right]. \quad \text{(I)}$$

If we designate, respectively, by S_θ, S_p, ..., S_α the partial sensitivities $dy/d\theta^{o}$; dy/dp; ... dy/dx*, and let $dy/dx = S_x$ and if we substitute these values into (I) we obtain

$$\Delta y = S_x \cdot \Delta x + S_\theta \cdot \Delta\theta^{\circ} + \cdots + S_\alpha \cdot \Delta\alpha$$

or

$$\Delta y = S_x\left[\Delta x + \frac{S_\theta}{S_x}\cdot\Delta\theta^{\circ} + \cdots + \frac{S_\alpha}{S_x}\Delta\alpha\right].$$

*In the general case the partial sensitivities are functions of all the acting quantities: $S_\theta = f'_\theta(\theta^{o}, p, \ldots\alpha)$; $S_p = f'_p(p, \theta^{o}, \ldots\alpha)$, etc.

The smaller the partial sensitivities S_θ, S_p, ... S_α, the smaller is the effect of external factors. /8

Sometimes, in addition to the relationship between the control quantity y and the input sensor parameter x, i.e., $y = f(x\ldots)$, we have the inverse relationship $x = \varphi(y)$.

Then

$$\Delta x_\Sigma = \Delta x + \frac{d\varphi}{dy}\Delta y;$$
$$y = f(x, \theta^\circ, p, \ldots \alpha)$$

and

$$\Delta y = S_x \cdot \Delta x + S_\theta \cdot \Delta\theta + \cdots + S_\alpha \cdot \Delta\alpha + S_x \cdot \frac{d\varphi}{dy}\Delta y.$$

Assuming that $d\varphi/dy = Sy$, we have

$$\Delta y = \frac{1}{1 - S_x \cdot S_y}\left[S_x \cdot \Delta x + S_\theta \cdot \Delta\theta^\circ + \cdots + S_\alpha \cdot \Delta\alpha\right].$$

The values of the partial sensitivities are usually not constant, but depend on the value of the actuating quantity, i.e., $S_\theta = f_1(\theta^\circ)$; $S_p = f_2(p)$; ... $S_\alpha = f_K(\alpha)$. These relationships are usually presented in graphical form.

10. It is important to know the magnitude of two limiting values for the quantities θ°, p, Z%, ... α: in one case, when the accuracy of the sensor does not exceed the assigned limits $\theta^\circ_{\lim_1}$, $p_{\lim_1}$, ... $\alpha_{\lim_1}$, and in another case, when the sensor is not destroyed or when the residual characteristics are retained: $\theta^\circ_{\lim_2}$, $p_{\lim_2}$ ... $\alpha_{\lim_2}$.

To eliminate the effect of external factors, two identical sensors are frequently used in a compensating (differential) scheme. In this case the basic control (input) parameter is fed to only one of them. In this case

$$\Delta y = [S_x \cdot \Delta x + S_{\theta_1} \cdot \Delta\theta^\circ + \cdots + S_{\alpha_1} \cdot \Delta\alpha_1] - [S_{\theta_2} \cdot \Delta\theta^\circ + \cdots + S_{\alpha_2} \cdot \Delta\alpha_2]$$
$$= S_x \cdot \Delta x + [(S_{\theta_1} - S_{\theta_2})\Delta\theta^\circ + \cdots + (S_{\alpha_1} - S_{\alpha_2})\,\Delta\alpha_2]$$

or, when $S_{\theta_1} \cong S_{\theta_2}$; $S_{p_1} \cong S_{p_2}$; ... $S_{\alpha_1} = S_{\alpha_2}$, we obtain $\Delta y \cong S_x\, \Delta x$.

11. The sensitivity of a sensor or of another component varies with its operating time (T), i.e., $S_x = \psi\,(T)$. In the general case /9

$$S_x = S_{x_0} + \frac{d\psi}{dT}\Delta T + \frac{d^2\psi}{dT^2}(\Delta T)^2 + \cdots \text{ etc.}$$

For $S_x = \psi\,(T)$ the following expressions are frequently quite accurate

$$S_x = S_{x_0} \cdot e^{-K_T \cdot T} \quad \text{or} \quad S_x = S_{x0_1} + S_{x0_2} \cdot e^{-K_T \cdot T}.$$

The value of K_T becomes high when the values of the following relative loads for individual parts of the sensor are high: the mechanical loads p_m/σ_{max} (where p_m is the mechanical pressure in different parts of the sensor; σ_{max} are the maximum permissible mechanical stresses), thermal loads $\theta^\circ/\theta^\circ_{max\ lim}$, magnetic loads B/B_{max} and electric loads E/E_{max}.

12. Volume V and the weight Q of a sensor are also important factors. It is most convenient to compare various sensors by using the ratios V/y_L and Q/y_L or the inverse quantities y_L/V and y_L/Q or the equivalent ratios P_{y_L}/V and P_{y_L}/Q, where y_n is the nominal value of the output quantity.

Section 2. Dynamic Properties and Characteristics

1. The relationship between the instantaneous values y and x during the transient process can usually be given in the form of a differential equation

$$a_0 \frac{d^n y}{dt^n} + a_1 \frac{d^{n-1} y}{dt^{n-1}} + \cdots + a_n y = b_0 \frac{d^m x}{dt^m} + b_1 \frac{d^{m-1} x}{dt^{m-1}} + \cdots + b_m \cdot x,$$

where m < n, or in operational form

$$(a_0 p^n + a_1 p^{n-1} + \cdots + a_n) y = (b_0 p^m + b_1 p^{m-1} + \cdots + b_m) x$$

or

$$\frac{y}{x} = \frac{[b_0 p^m + b_1 p^{m-1} + \cdots + b_m]}{[a_0 p^n + a_1 p^{n-1} + \cdots + a_n]}$$

This relationship is known as the transient function of the element.

Figure 4 shows the variation (time characteristic) in the output signal /10 quantity (y) during the stepwise variation of the input quantity (input signal) (x = I).

The following quantities are significant in evaluating the dynamic properties of the element: the delay time ("dead time") T_0 (fig. 4), the rise time T_1 and the total transient time T_t. The total transient time T_t is the interval

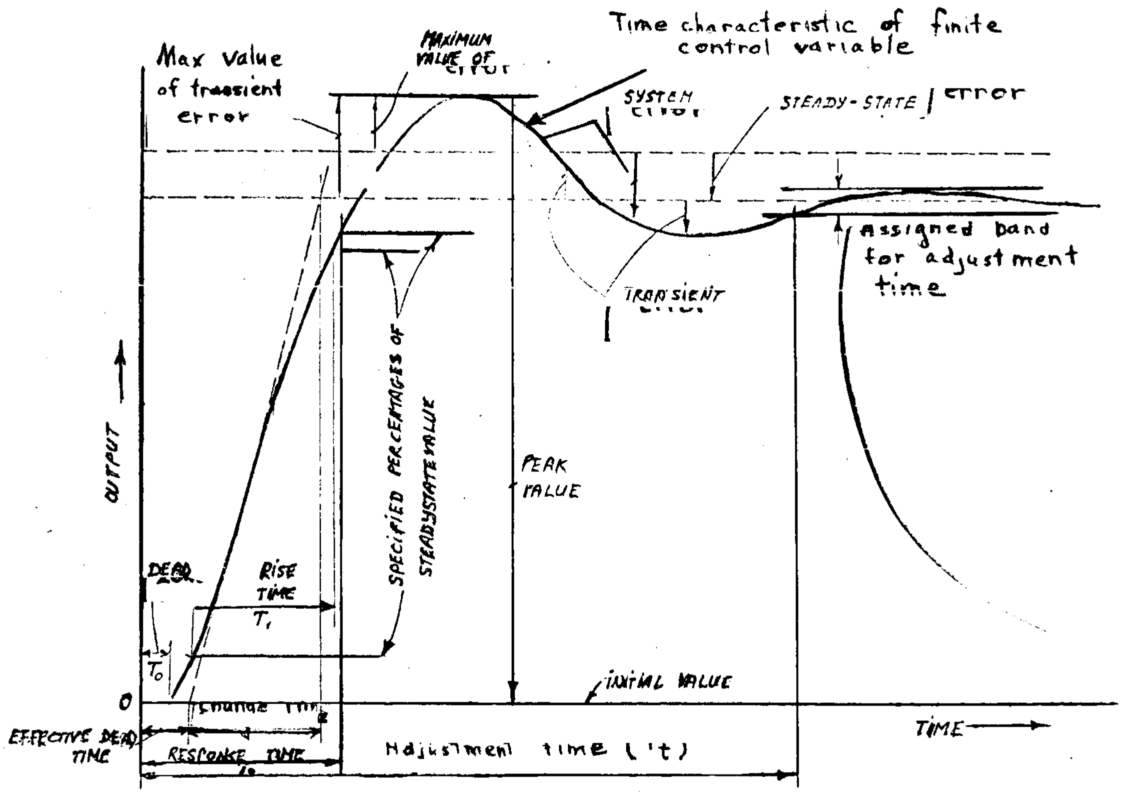

Figure 4

of time from the start of the transient process to the achievement of a steady state value for the output quantity (output signal). The accuracy of the steady state value of the output signal is determined by the error of the element.

By taking into account the delay time, the time characteristic can be represented in the form

$$W(p) = \frac{y}{x} = \frac{e^{-T_t p}}{a_0 p^n + a_1 \cdot p^{n-1} + \dots + a_n}$$

If the sensor is under a continuous action of parameter x given by $x = X_m \cdot \sin \omega t$ or $x = \dot{X}_m \cdot e^{j\omega t}$, then $y = \dot{Y} \cdot e^{j\omega t}$, and by substituting values x and y into the preceding expressions, we obtain

$$W(j\omega) = \frac{\dot{Y}_m}{\dot{X}_m} = \frac{1}{a_0 (j\omega)^n \ a_1 (j\omega)^{n-1} + \dots + a_n}$$

This relationship is known as the amplitude-phase characteristic (fig. 5). Instead of this characteristic the amplitude-frequency and the phase-frequency characteristics are frequently used. They are obtained from the amplitude-phase characteristic, if the denominator is represented in the form

$$a_0 (j\omega)^n + a_1 (j\omega)^{n-1} + \dots + a_n = A(\omega) + jB(\omega)$$

Then the amplitude-frequency characteristic will be given by the expression

$$A(\omega) = |W(j\omega)| = \left|\frac{\dot{Y}_m}{\dot{X}_m}\right| = \frac{1}{\sqrt{A^2(\omega) + B^2(\omega)}};$$

and the phase-frequency characteristic will be given by the expression

$$\varphi = \operatorname{arctg} \frac{B(\omega)}{A(\omega)}.$$

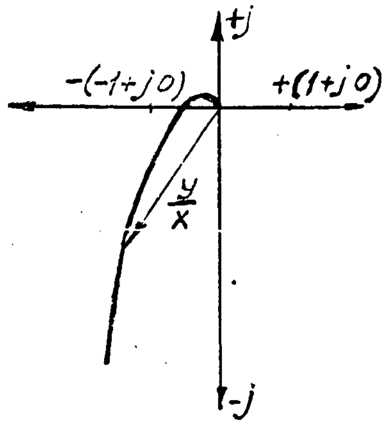

Figure 5. Amplitude-phase characteristics.

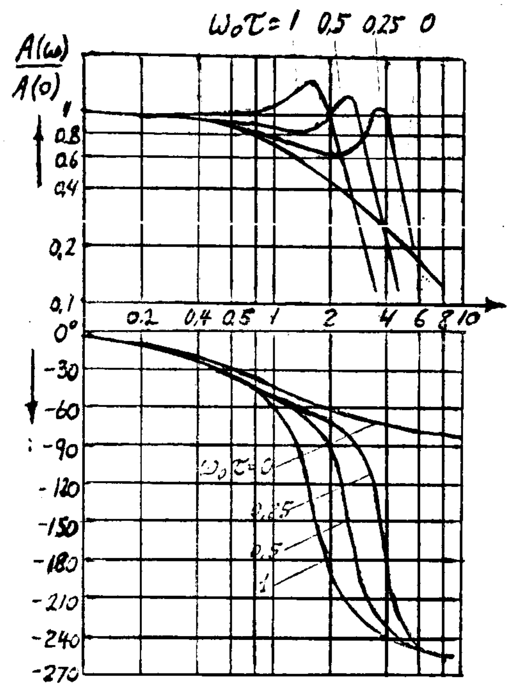

Figure 6.

Let us assume for example that $\omega = \omega_0 = 0$, then /13

$$|W(0)| = \left|\frac{y_m}{X_m}\right|_{\omega=0} = \frac{1}{a_n} = S_x$$

and the ratio of $W(\omega)$ to $W(0)$ is given by $W(\omega)/W(0) = \left|\frac{a_n}{\sqrt{A^2(\omega)+B^2(\omega)}}\right|$.

If, following the conventional practice, we construct the function $W(\omega)$ to a logarithmic scale, we obtain the so-called logarithmic amplitude-frequency characteristic (fig. 6).

2. In addition to elements which give a linear relationship (fig. 7a), frequent use is made of elements which give an integral and a differential relationship between the output and input quantities. /14

For elements with an integral relationship (fig. 7b) we have

$$K_I = S_I = \frac{y_2' - y_1'}{x_2 - x_1} = \frac{\Delta\left(\frac{dy}{dt}\right)}{\Delta x};$$

and for elements with a differential relationship (fig. 7c) we have

$$K_D = S_D = \frac{y_2 - y_1}{x_2' - x_1'} = \frac{\Delta y}{\Delta\left(\frac{dx}{dt}\right)} \quad .$$

In complex elements, used as regulators, combined relationships are usually used which are achieved by

(a) PI elements

$$y(t) = K_P\left[x(t) + \frac{1}{T_I}\int_0^t x(t)\,dt\right], \text{ where } K_p = S.$$

In symbolic form, by neglecting the numbers with higher frequencies, this can be represented as

$$\frac{Y}{X} = \pm K_P \frac{\frac{1}{j\omega T_I}}{\frac{b_0}{j\omega T_I} + 1} \quad \text{when } 0 \le b \ll 1,$$

where B_o is the ratio of the amplification factor in the linear circuit to the static amplification factor;

T_I is the time constant of the integrating network (fig. 8).

(b) PD elements

$$y(t) = K_P\left[x(t) + T_D \frac{dx(t)}{dt}\right], \text{ where } K_p = S,$$

or in symbolic form, by neglecting terms with higher frequencies,

$$\frac{Y}{X} = \pm K_P \frac{1 + j\omega T_D}{1 + \frac{j\omega T_D}{K_D}} \quad \text{when } a > 1,$$

where K_D is the amplification of the derivative; /15

T_D is the time constant of the differential network (fig. 9).

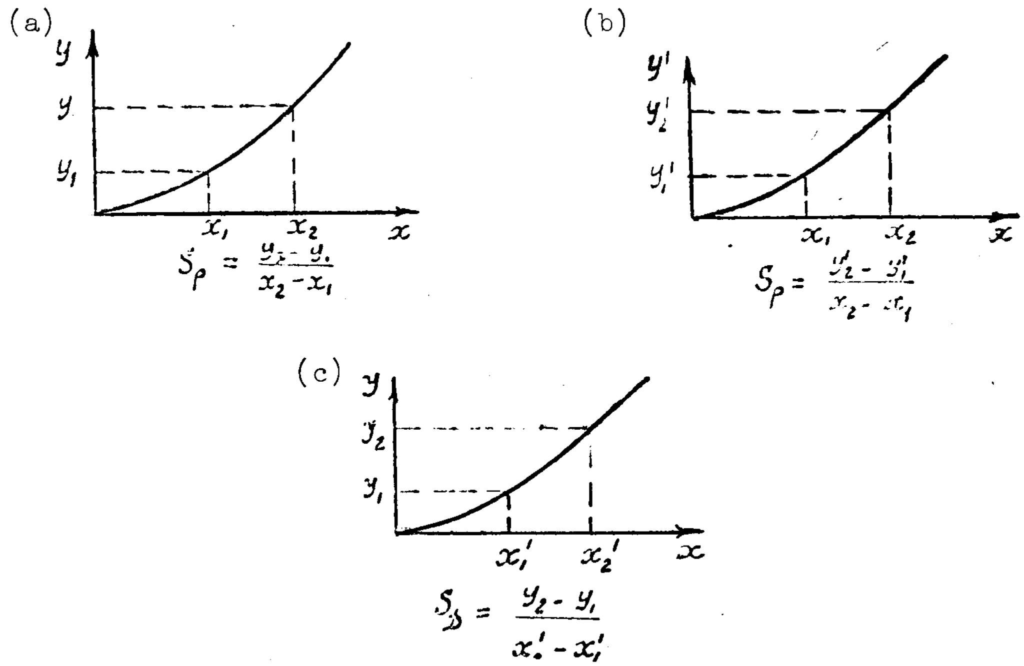

Figure 7

(c) PID elements

$$y(t) = k\left[a_0 x(t) + \frac{1}{T_I}\int_0^t x(t)\,dt + T_D \frac{dx(t)}{dt}\right],$$

where

$$a_0 = 1 + T_D/T_I ,$$

or in symbolic form, by neglecting terms with higher frequencies,

$$\frac{Y}{X} = \pm K_p \frac{\frac{1}{j\omega T_I} + 1 + j\omega T_D}{\frac{b_0}{j\omega T_I} + 1 + \frac{j\omega T_D}{K_D}}$$ when a > 1 and 0 ≤ b < 1,

K_D is the amplification of the derivative;

b_0 is the ratio of the amplification factor in the linear circuit to the static amplification factor;

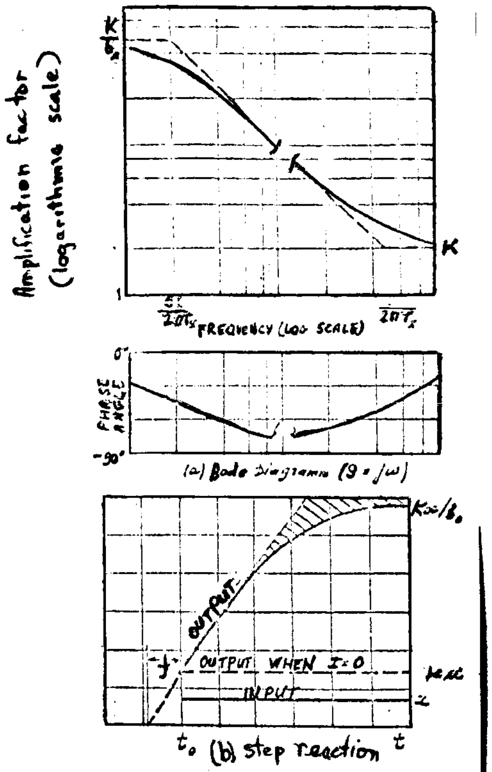

Figure 8

T_D is the time constant in the differentiating network;

T_I is the time constant in the integrating network (fig. 10).

3. Table 2 shows the dynamic characteristics for the basic types of elements.

4. A distinction is made between the elements with nonadjustable dynamic characteristics and elements with adjustable characteristics. In the latter one or several parameters may vary

$$a, b, T_D, I, P.$$

5. We should bear in mind that this examination of the frequency characteristics may be applied not only with respect to the input parameter x, but also with respect to any of the quantities acting on the sensor (θ^o, Z%, ... α).

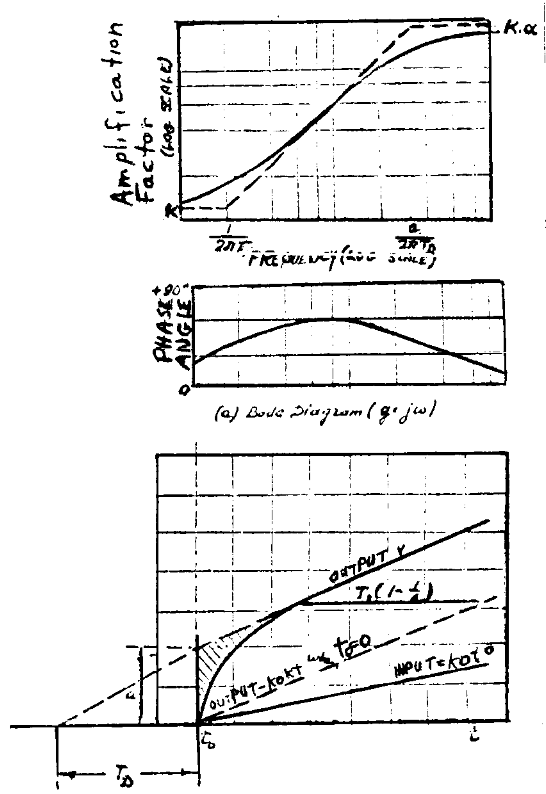

Figure 9

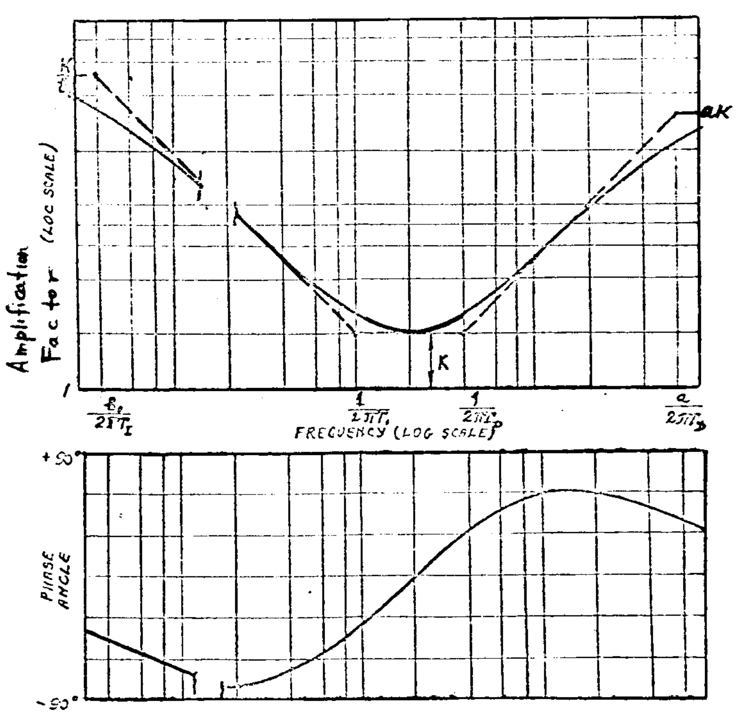

Figure 10

Section 3. Error /17

The functional characteristics are not sustained accurately due to the presence of various forms of static and dynamic errors.

I. Static Errors

Static errors can be divided into determined errors and undetermined (random) errors.

A. The determined errors of the elements in automatic control equipment include the following

1. Methodical errors

1.1. The methodical errors are caused by the use of an approximate functional relationship $y = f(x)$ in place of the necessary functional relationship $y = f_0(x)$.

The values of the methodical error Δy_m are determined as /18

$$\Delta y_m = f_0(x) - f(x).$$

1.2. The methodical error can be subdivided into the basic error determined when the external factors (θ°_0, $Z_0\%$, a_0) are constant (assigned, "normal") and a complementary error produced by the variation of external factors (θ°, $Z\%$, a, ...).

2. Instrumental Errors

2.1. When the external conditions are unchanged, the relation between the output and input quantity, taking into account hysteresis, may be represented in the form

$$y = f(x) \pm \Delta y_h.$$

Taking into account the spread in the values of each term and assuming that the spread in the values follows, for example, the normal law

$$f(x) = \overline{f(x)} \pm n\sigma_1$$

and

$$\Delta y_h = \Delta \overline{y}_h + n\sigma_2 \quad ,$$

we find that

$$y = \overline{f(x)} \pm \overline{\Delta y_h} + n\sigma_\Sigma \, ,$$

where $\sigma_\Sigma = \sqrt{\sigma_1^2 + \sigma_2^2}$

Usually a linear relationship between the output and input parameters is required

$$y_i = S \cdot x \, .$$

Assuming that S = S + nσ_3, and taking into account the possibility of the displacement at the initial point of the characteristic, we have

$$y_i = [\bar{S} + n\sigma_3] \cdot (x - x_0) = \bar{S}(x - x_0) + n\sigma(x - x_0),$$

In addition, we should take into account the variation in the value of $\bar{S}$ as a function of time, i.e., we must assume that

$$\bar{S} = \bar{S}_0 + \frac{\Delta \bar{S}_0}{\Delta t} \cdot t,$$

and we obtain /19

$$y_i = \bar{S}_0 (x - x_0) + \frac{\Delta \bar{S}_0}{\Delta t} (x - x_0) \cdot t + n\sigma (x - x_0) .$$

The instrumental error is determined as

$$\Delta y = y - y_i$$

or

$$\Delta y = [f(\bar{x}) \pm \Delta\bar{y}_h + n\sigma_x] - [\bar{S}_0(x-x_0) + \frac{\Delta\bar{S}_0}{\Delta t}(x-x_0)t + n\sigma(x-x_0)].$$

By determining $\sigma'_x = \sqrt{\sigma_x^2 + (x-x_0)^2\sigma^2}$, we obtain the maximum instrumental error

$$\Delta y = \underbrace{\underbrace{\underbrace{[f(\bar{x}) - S_0(x-x_0)]_{max}}_{\text{error due to nonlinearity}} + \underbrace{\Delta\bar{y}_{h\,max}}_{\text{error due to hysteresis}} + \underbrace{\left[\frac{\Delta S_0}{\Delta t}(x-x_0)t\right]_{max}}_{\text{drift}}}_{\text{determined errors}} + \underbrace{n\sigma'_x}_{\text{random errors}}}_{\text{variation}}$$

The individual components of the determined error may be established in the following manner.

2.1.1. The error due to hysteresis and dry friction can be determined as the maximum difference for the average of a series of measurements of the output signal when the input signal remains constant, while there is an increase and a decrease in the output signal, i.e.,

$$\Delta y_1 = \frac{1}{2}\left|\frac{\sum_1^n y_x^{\uparrow}}{n} - \frac{\sum_1^n y_x^{\downarrow}}{n}\right|_{max},$$

or $\Delta y_1 = \frac{1}{2}[\bar{S}_0 \Delta x_h]_{max}$, where Δx_h is the width of the hysteresis loop.

The relative error due to hysteresis is determined as /20

$$\delta_1 = \Delta y_1 / y_{max}$$

2.1.2. The error due to nonlinearity for elements with a linear characteristic are determined as the maximum deviations of the true curve $y = f(\overline{x})$ from the straight line, i.e.,

$$\Delta y_2 = \left| f(\overline{x}) - \overline{S}_0 (x - x_0) \right|_{max} .$$

The relative error due to nonlinearity is equal to $\delta_2 = \frac{\Delta y_2}{y_{max}}$.

2.1.3. The dead zone is the minimum value of the input signal which produces an output signal.

2.1.4. Drift is usually determined as the maximum deviation of the output parameter when the value of the output parameter is x = 0 during an assigned interval of time $t = t_0 = 1$ hr, $t_0 = 8$ hr, $t_0 = 24$ hr, etc. $\Delta y_3 = \left| \frac{\Delta \overline{S}_0}{\Delta t} x_0 \cdot t_0 \right|_{max}$.

2.1.5. The variation is equal to the maximum value of half the difference between the maximum and minimum values of the output signal, obtained by a series of measurements of the same value of the input signal (x = const) as it rises to a maximum value and decreases to a minimum value when external factors are constant.

The value of the input signal x = const is taken for a series of values $x = x_1$, $x = x_2$, ... between $x = x_{min}$ and $x = x_{max}$; the local variations for the input signal $x = x_1$, $x = x_2$, ... are determined; the maximum value of these is the variation. The variation determines the error incurred in reproducing the values of input signals (with an input signal x = const) with repeated signals supplied to the element during a short period of time while the aging processes still have no effect.

2.2. The complementary instrumental errors due to the variation of external factors (complementary error).

The absolute value of this error is equal to /21

$$\Delta y_{ef} = S_{\theta}\cdot\Delta\theta^{\circ} + S_{z}\cdot\Delta z + \cdots + S_{\alpha}\cdot\Delta\alpha = \Sigma S_{i}\cdot\Delta x_{i} ,$$

(subscript ef = external factors)

while the relative error is equal to $\delta_{ef} = \Delta y_{ef}/y_{max}$.

2.3. The spread (scatter, dispersion). Instrumental errors do not remain constant for different samples of the element, since the values S_x, S_θ, ... S_α cannot be strictly constant.

2.4. Fidelity. Instrumental errors change with time since S_x, S_θ, ... S_α vary with the operation time of the element.

II. Dynamic Errors

Dynamic errors which occur during the transient process are determined as

$$\Delta y(t) = y_k - y(t),$$

where y_k is the required value of the output quantity at the instant of time t,

$$y_k = S_x \cdot x(t);$$

$y(t)$ is the true value of the output quantity at the time instant.

For a linear element we have

$$\Delta y(t) = x(t)\left[S_x - \frac{y(t)}{x(t)}\right].$$

Or, conversely, by assuming that $y(t) = K(p)\cdot\Delta y(t)$ we obtain

$$\Delta y(t) = y_k - y(t) = y_k - K(p)\cdot\Delta y(t),$$

or

$$\Delta y(t) = \frac{y_K}{1+K(p)}.$$

The maximum value of the dynamic error during the first extreme value (i.e., if we do not take into account the initial instant of time when it is equal to $-y_K$) which is equal to $\Delta y(t)_{max}$ is called the overshoot.

During the sinusoidal variation of the input signal with frequency /22 ω_i we have

$$\Delta y(\omega_i) = \frac{y_K(\omega_i)}{1+K(j\omega_i)} = \frac{y_K(\omega_i)}{1+C(\omega_i)+jB(\omega_i)}.$$

The maximum error is determined as

$$\Delta y(\omega_i)_{max} = \frac{y_K(\omega_i)_{max}}{\sqrt{[1+C(\omega_i)]^2 \cdot B^2(\omega_i)}},$$

and in this case the phase shift is equal to

$$\varphi_i = \operatorname{arctg} \frac{B(\omega_i)}{1+C(\omega_i)}.$$

Section 4. Information Characteristics

The elements of automatic devices are used to obtain transformations, to store, shape and utilize information. Therefore it is necessary to evaluate an element from the point of view of its information characteristics; for this purpose we can use a quantity which characterizes the information flow

$$F = \Delta f \cdot \log_2 \left(1 + \frac{x_{max} - x_{min}}{\Delta x_\Sigma}\right),$$

where Δf is the width of the passband;

x_{max}, x_{min} are the upper and lower limits of the input parameter;

Δx_Σ is the total static error.

We can introduce certain cumulative characteristics of sensors proceeding from the following considerations. We can take a point on the amplitude-frequency characteristic $W(\omega) = \psi(\omega)$ which corresponds to a decrease in $W(\omega)$ to some assigned value, for example, $W(\omega)/W(0) = 0.9$ or 0.7 or 0.5, etc., which has a corresponding $S_x = S_{xn}$ and an angular frequency $\omega = \omega_n$ or $f_n = \omega_n/2\pi$. The product $Q = S_{xn} \cdot f_n$ simultaneously defines the static as well as the dynamic sensitivity. If in place of the value S_{xn} we take S_{xo}, then $Q_o = S_{x_o} \cdot f_n$. If the quantity F is multiplied by the time corresponding to the operating time of the element T_c, we obtain a new measure

$$A = \Delta f \cdot T_c \log_2\left[1 + \frac{x_{max} - x_{min}}{\Delta x_x}\right],$$

which characterizes the quantity (volume) of information received by the sensor during its entire operating time. /23

Finally the quantity equal to $M = S_x \cdot \Delta f \cdot \log_2\left[1 + \frac{x_{max} - x_{min}}{\Delta x_x}\right]$, is a cumulative parameter which characterizes the basic parameters of the sensor: S_x - sensitivity (S_{xn} or S_{xo}),

x_{max} and x_{min} are operating limits,

Δf is the boundary operating frequency band.

Section 5. Reliability

One of the basic parameters of an element is reliability, i.e., the probability associated with the proper operation of the element. The quantitative value of reliability is determined as the probability of achieving an assigned function under assigned conditions; the quantity depends on the design factors, time and operating mode of the element.

Reliability is distinguished as pertaining to total (catastrophic, sudden) failures R_a and reliability with respect to incomplete (gradual) failures R_b.

1. The value of reliability R_a (fig. 2) is determined as

$$R_a = e^{-\int_0^t \lambda dt},$$

and for λ = const it is determined as $R_a = e^{-\lambda t}$, where λ is the intensity ("danger") of failures equal to

$$\lambda = \frac{dn_x}{dt} \cdot \frac{1}{n_x} = -\frac{dR_a}{dt} \cdot \frac{1}{R_a}.$$

The value of the intensity ("danger") of failures may be represented in the form

$$\lambda = \lambda_0 \cdot K_p \cdot K_\theta \cdots,$$

where λ_0 is the intensity of failures in the nominal operating state, while K_p, K_θ are correction factors which take into account the variation in λ when there is a change in the load (P), temperature (θ°), humidity (Z%) and in other factors from their nominal values. The values K_p, K_θ, ... are usually assigned graphically.

2. The value of the reliability R_b for an analog element is determined as the probability that the true value of the output signal y correspond to /24
its design value $y = S_x \cdot x$ (when x = const) with an assigned accuracy $\frac{\Delta y_x}{y_{max}} = const = \delta_x = \delta$.

At the beginning of the operation the assigned accuracy $\pm \delta = \frac{\Delta y_x}{y_{max}}$ corresponds to $R_b = 0.997$, when $\delta = \pm 3\sigma$ (fig. 12).
With time the value of $S_x = S_{x_0} + \frac{\partial S_x}{\partial T} T$ varies, which causes a displacement in the value of $y = S_x \cdot x$ by an amount $\Delta y = (S_{x_0} - S_x) \cdot x$, and the band $2\delta = 6\sigma$ will now be associated with a value $R_b < 0.997$.

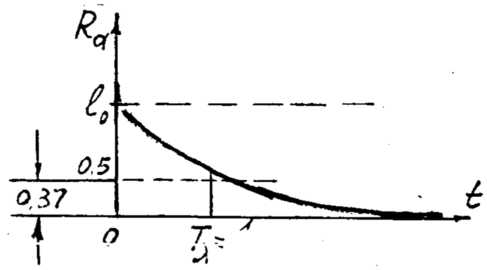

Figure 11. Curve showing variation in reliability as function of time for total element failures.

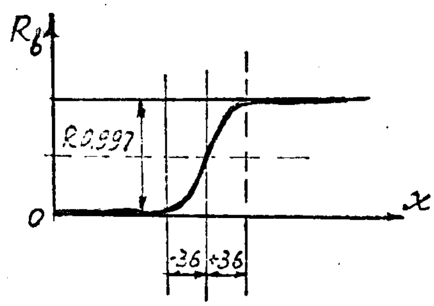

Figure 12. Variation in reliability for incomplete analog element failures.

3. The resultant reliability of the analog element, which is determined as the probability of proper operation with an assigned accuracy, involves the coincidence of two events--the proper operation of the element in general (R_a) and its operation with required accuracy (R_b), i.e.,

$$R = R_a \cdot R_b .$$

The reliability parameter is closely associated with two other parameters, the technical resource and operating life. /25

Technical Resource. T_T is the sum of time intervals associated with failure-free operation of the system or of the device during its period of exploitation, until breakdown or some other limiting condition occurs.

Remarks: It is possible to distinguish between the "total technical resource" which is measured from the beginning of the exploitation, a "residual technical resource," which is measured from a specific instant of exploitation and an "average technical resource" which is the average value of the total technical resource of a given system or device.

The "guaranteed resource" is the technical resource which is exhibited by not less than γ percent of the exploited systems or devices where γ is a guaranteed probability.

Useful Life. T_c is the calendar longevity of system or device exploitation until it breaks down or attains some other limiting state.

Remarks: It is possible to distinguish between the "average life" as the average calendar longevity of system or device exploitation until breakdown or some other limiting state and "a guaranteed life" as the calendar longevity of system or device exploitation, during which the manufacturing plant is responsible for any malfunctions occurring during exploitation, notwithstanding the adherence to proper operating procedures.

For elements which can be put back into operation by appropriate repairs a technical preparedness factor K_T is introduced, equal to

$$K_T = \frac{T_T}{T_T + \Sigma t_p},$$

where t_p is the repair time.

The quantity characterizing the probability of sound operation is then determined as

$$P = R \cdot K_T.$$

PART II. BASIC CHARACTERISTICS AND PARAMETERS OF SWITCHING ELEMENTS

Section 1. Static Parameters and Characteristics

The static characteristics of switching elements (fig. 13) include the following: /26

1. The operate parameters. X_a - the average value of the input signal (X) for which the element goes from the inoperative to the operative state.

2. The reset parameter X_b - the average value of the input signal (X) for which the element returns to its initial state.

3. The ratio $X_b/X_a = K_b$ is called the reset factor.

4. The operating parameter X_p - the value of the input signal (X) selected as the nominal (operating) signal.

5. The factor of safety during operation is equal to the ratio $X_p/X_a = K_p$, while the factor of safety during release is equal to the ratio $X_b/X_0 = K_p'$. Here X_0 is the residual value of the input signal.

6. Control factor - $K_c = y_{max}/X_a$.

7. The multiplicity factor is determined as $K_k = y_{max}/y_{min}$ where y_{max} corresponds to $X \geq X_a$ (usually when $X = X_p$) while y_{min} corresponds to $X \leq X_b$ (usually when $X = X_0$).

8. The switching elements can be adjustable or nonadjustable. In the latter case the values X_a, X_b, K_k can vary.

9. For noncontact elements the transfer characteristics (of signals) are used ("input-output" characteristics; fig. 14a and b) /28

$$\left(\frac{y}{y_{max}}\right) = f\left(\frac{x}{x_{max}}\right).$$

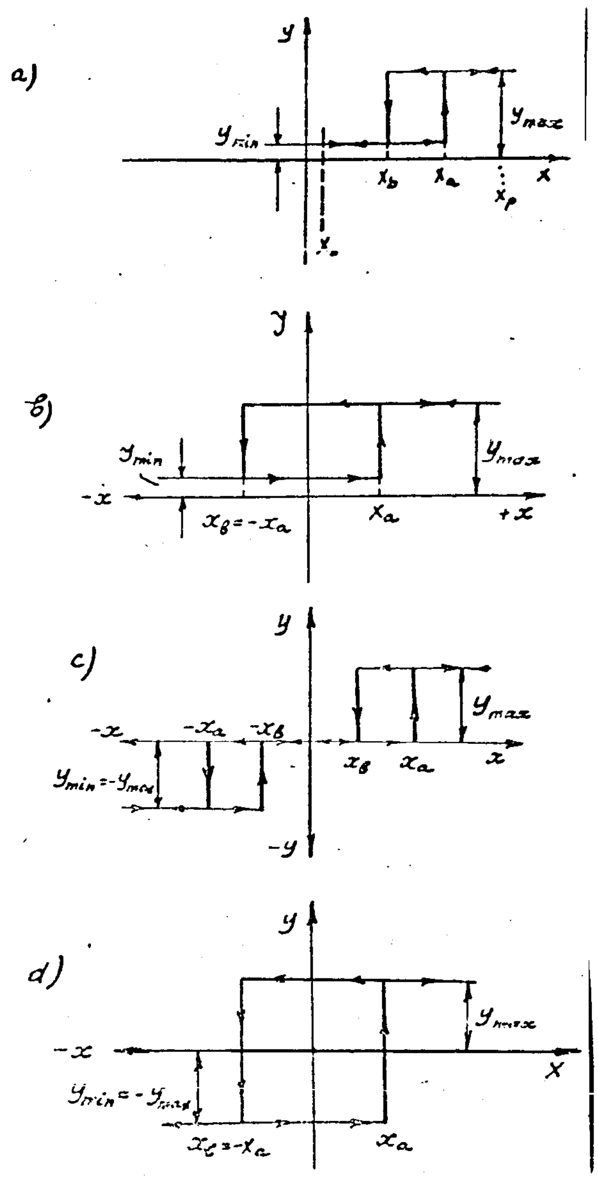

Figure 13

Points a and c correspond to the nonoperative ("zero") and operative ("unity") state of the element. In case of a "repeater" element, the "zero" state corresponds to $(y/y_{max}) \approx 0$, while the state "unity" corresponds to the value $(y/y_{max}) \approx 1$; with an "inverter" element we have a corresponding value $(y/y_{max}) \approx 1$ during the "zero" state and $(y/y_{max}) \approx 0$ for the "unity" state.

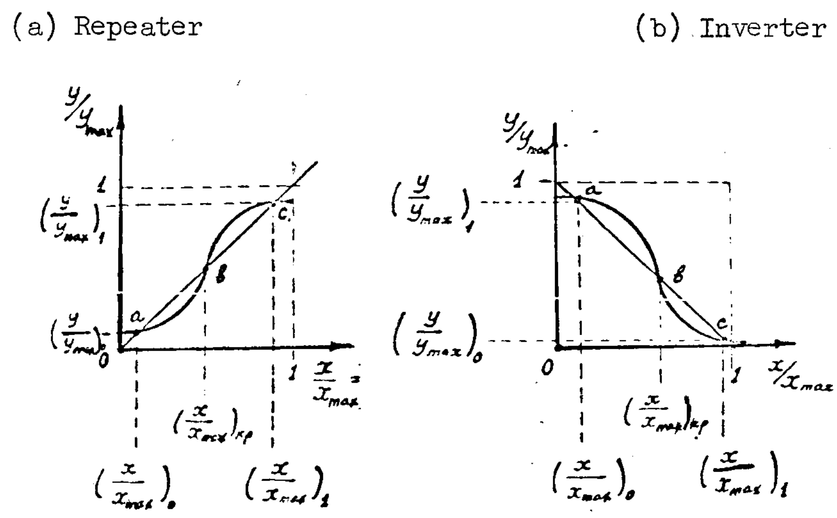

Figure 14

An important parameter is the value $(X/X_{max})_{Kp}$ which is the critical value of the relative magnitude of the input signal. It is important to know the variation in $(X/X_{max})_{Kp}$ as a function of various factors, such as voltage, temperature, operating time, etc.

$$\left(\frac{x}{x_{max}}\right)_{kp} = \left(\frac{x}{x_{max}}\right)_{kp_0} + \Delta_V\left(\frac{x}{x_{max}}\right)_{kp_0} + \Delta_\theta\cdot\left(\frac{x}{x_{max}}\right)_{kp_0} + \cdots$$

In addition to this it is important to know the spread in the values $(X/X_{max})_{Kp_0}$ (for "normal" values: V, θ^0, ...) for various samples of the /29
elements. Usually the spread in the values $(X/X_{max})_{Kp_0}$ is made to conform to the normal distribution law. Therefore, it is important to know the average value of $(X/X_{max})_{Kp_0}$ and the root-mean-square deviation σ.

10. The boundary characteristics are the characteristics which determine the limits of permissible values for individual parameters of external reactions for which the operation of the element is possible.

To determine the boundary characteristics, all parameters of external reactions U_i are preset to a fixed (initial) state. The element is connected to

(a) Conditions for determination of boundary characteristics

(b)

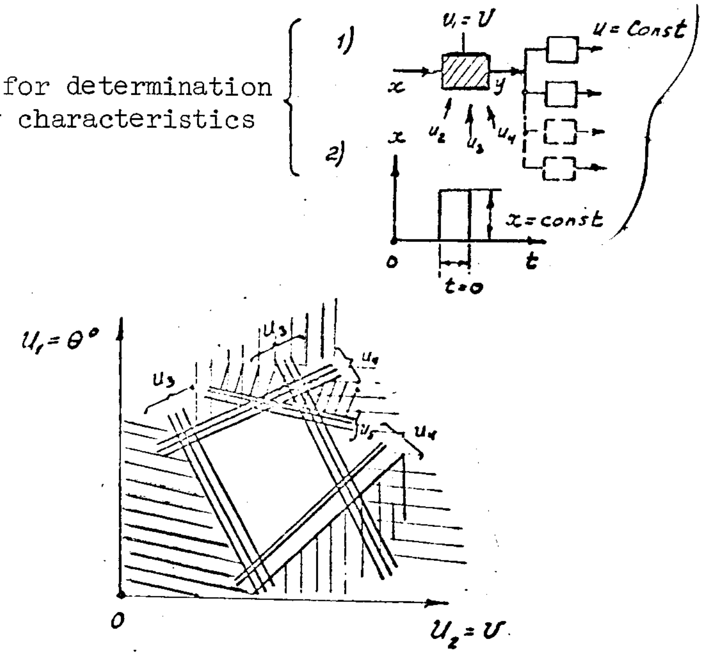

Figure 15

the circuit which contains an assigned load at the output (the assigned number of other elements is n = 1, 2 ...). The input of the element is fed with an assigned quantity for an assigned period of time ("normal" or "minimum").

By assigning a series of values U_1 for one of the U - parameters (for example, $U_1 = \theta^o$), the value of another parameter U_2 (for example, U_2 = V) /30 is established, for which the element ceases to function properly (under assigned input and output conditions). The values which are obtained are plotted on a graph of $U_2 = f(U_1)$ and a curve is drawn through these points. Several measurements of the third parameter U_3 are taken and U_1 and U_2 are determined for which the elements cease to work. This is repeated for several values of parameter U_4 and for several values of parameter U_5, etc.

The curves which join the obtained values of parameters U_1 and U_2 with fixed variations of parameters U_3, U_4, U_5 ..., are the boundary characteristics (fig. 15). The region lying inside the boundary characteristics determines the permissible variations of the parameters.

Section 2. Dynamic Characteristics

The dynamic parameters and the characteristics of switching elements include the following:

1. (a) The operate time t_a - the interval of time from the application of the input signal to the appearance of the output signal;

(b) The reset time t_b - the interval of time from the determination of the input signal to the cessation of the output signal.

The operate time (t_a) is a function $t_a = f_1 (K_p)$ of the safety factor K_p; the reset time (t_b) is a function $t_b = f_2 (K_p)$ of the safety factor K_p.

The functions $t_a = f_1 (K_p)$ and $t_b = f_2 (K_p)$ (fig. 16) depend on the time constants τ_a and τ_b which are determined by the design and parameters of the circuit for the input signal. The time constants τ_a and τ_b correspond to the variation $\frac{\Delta x}{x_{max}} \hat{=} e^{-1} = 0.63$.

2. The elements can have adjustable or nonadjustable time characteristics. In the former case the following characteristics are assigned: $t_a = f_{12} (K_p, Z)$ and $t_b = f_{22} (K_p, Z)$, , where Z is the value of the adjustment parameter.

3. The characteristic showing the variation in the ratio of operate time to reset time as a function of the input quantity (input signal) are given by: $t_1/t_2 = f (X)$. /31

The switching of the noncompact elements from the "zero" state to the "unity" state and from the "unity" state to the "zero" state takes place during a period T, which for many types of noncontact elements (magnetic, dielectric) may be considered as equal to

$$T = \frac{S_w}{[x - x_0]},$$

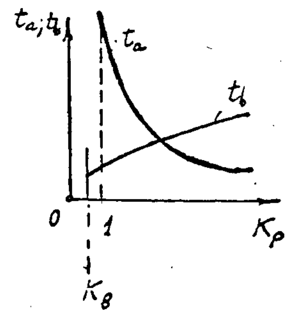

Figure 16

where S_w is a constant which depends on the material and design of the elements;

X_0 is the limiting value of the input quantity.

Section 4*. Reliability

1. Since the individual errors have a constant and a random component, the spread in the values of operate parameters and reset parameters have a form shown in figure 17. Usually the operate probability and the reset probability follow the normal law. Therefore, if the operating values of the input parameter X_p are assigned as well as the zero value X_0, the operate probability (i.e., reliability) R'_b and the reset probability R''_b are determined (fig. 17) as

$$R'_b = \frac{1}{\sigma_a\sqrt{2\pi}}\int_{-\infty}^{x_p} e^{-\frac{(x_a-\bar{x}_a)^2}{2\sigma^2}}\,dx,$$

while

$$R''_b = 1 - \frac{1}{\sigma_b\sqrt{2\pi}}\int_{-\infty}^{x_0} e^{-\frac{(x_b-\bar{x}_b)^2}{2\sigma^2}}\,dx.$$

[*Section 3 not given in the original text.]

2. After a period of time, and also due to external factors such as temperature, radiation, humidity, acceleration and others, there is a change in the values /32

$$\bar{x}_a = \bar{x}_{a_0} + \Delta\bar{x}_a = \bar{x}_{a_0} + \left[\frac{d\bar{x}_a}{dT}\Delta T + \frac{d\bar{x}_a}{d\theta^\circ}\cdot\Delta\theta^\circ + \cdots\right]$$

and

$$\bar{x}_b = \bar{x}_{b_0} + \Delta\bar{x}_b = \bar{x}_{b_0} + \left[\frac{d\bar{x}_b}{dT}\Delta T + \frac{d\bar{x}_b}{d\theta^\circ}\Delta\theta^\circ + \cdots\right].$$

This produces a change in the operate and reset probability of the element. The probability that the element will operate and become reset for given values X_p and X_0 is equal to

$$R_b = R_b' \cdot R_b''.$$

3. In addition to failures in operation due to the spread in the operate and reset parameters of the element, and due to their variation with time and under the action of external factors (temperature, radiation, humidity, etc.), it is also necessary to take into account sudden failures, which are determined by the relationship $R_a = e^{-\lambda t}$, where λ is the rate ("danger") of failures.

The value of λ depends on the operating mode of the element and on the action of external factors (temperature, radiation, humidity, etc.) i.e., $\lambda = \lambda_0 \cdot K_p \cdot K_\theta \ldots$, where

$$K_p = \varphi_1(P_x/P_H);\ K_\theta = \varphi_2(\theta^\circ - \theta_H^\circ),\ \text{etc.}$$

while λ_0 is the rate ("danger") of failures under nominal values of the load, temperature, humidity, etc.

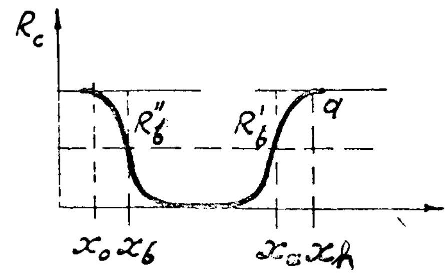

Figure 17. Variation in reliability for incomplete failures of switching elements.

4. The resultant reliability of a switching element is equal to

$$R = R_a \cdot R_{\text{б}}$$

APPENDIX 1. PERFORMANCE CHARACTERISTICS

Of the basic criteria which are used to select devices and equipments for automatic control, protection, regulation and control, the following performance factors are frequently considered. /33

1. The cost of the element (device, equipment)

$$C_{1x} = C_x \cdot n_x \cdot \frac{T_c}{T_x},$$

where C_x is the cost taking into account the shipping costs, installation costs and adjustment costs;

n is the number of identical elements in a functional system;

T_c is the useful life of the industrial setup;

T_x is the useful life of the element.

By using this expression it is possible, when evaluating the costs of comparable elements, to introduce a correction for the useful life of an element (device, automatic equipment). In this connection it is important to take into account the useful life not in the absolute expression, but in relation to the useful life of the basic industrial setup.

The cost of all elements of a functional system during the useful life of the installation is given by expression

$$C_1 = \sum_{x=1}^{x=m} C_x \cdot n_x \cdot \frac{T_c}{T_x},$$

where m is the number of element groups which compose the functional system.

2. The cost of additional energy and additional material required for the operation of the elements is given by

$$C_2 = \sum_{x=1}^{x=m} C_{yx} \cdot n_x \cdot T_c ,$$

where C_{yx} is the cost of energy and auxiliary materials for one hour of element operation.

3. The operating costs are given by /34

$$C_3 = \frac{N}{N_0} C_z \cdot T_c ,$$

where N is the total number of elements;

N_0 is the number of elements per individual of the service staff;

C_z is the average cost per man-hour.

4. The possible cost due to losses in the technological process caused by the breakdown of individual elements is given by expression

$$C_4 = \sum_{x=1}^{x=m} n_x \cdot C_0 \cdot q_x , \text{ где } q_x = 1 - R_a = 1 - e^{-\lambda t} \cong \lambda t = \lambda T_c$$

The total cost is given by the expression

$$C_\Sigma = \sum_{K=1}^{K=4} C_K = \sum_1^m C_x \cdot n_x \frac{T_c}{T_x} + \sum_1^m C_{yx} \cdot n_x T_c + \frac{N}{N_0} C_z T_c + \sum_1^m n_x \cdot C_0 \cdot \lambda_x T_c .$$

TABLE 1. PART 1. BASIC CHARACTERISTICS AND PARAMETERS OF ANALOG CONVERTER ELEMENTS.

№ п/п	Designation	Terms	
I	2	3	4
	I. Statistical parameters and characteristics		
I	$y = f(x)$	характеристика управления	control characteristics
2	x_{min}	нижний предел входного параметра	lower limit, input param.
	x_{max}	верхний предел входного параметра	upper limit, input param.
	y_{min}	нижний предел выходного параметра	lower limit, output param.
	y_{max}	верхний предел выходного параметра	upper limit, output param.
	$P_{x\,min}$	нижний предел подводимой мощности	lower limit, input power
	$P_{x\,min}$	верхний предел подводимой мощности	upper limit, input power
	$P_{y\,min}$	нижний предел управляемой мощности	lower limit, control power
	$P_{y\,max}$	верхний предел управляемой мощности	upper limit, control power
3	$x_{max\,lim}$	предельно допустимая величина входного параметра	safety limit, input param.
	T_{lim}	предельно допустимое время воздействия входного параметра	time limit, input param.
4	$\frac{y}{x} = S$	"общая чувствительность"	total sensitivity
	$\frac{\Delta y}{\Delta x} = S'$	дифференциальная чувствительность	differential sensitivity
5	$R_x = F(X)$	"сопротивление"	resistance
	$K_x = F_1(X)$	"условная проводимость"	specific admittance
6	$\bar{Z}_{вх}$	входное сопротивление	input impedance
	$\bar{Z}_y$	выходное сопротивление	output impedance
7	$\frac{dy}{d\theta}, \frac{dy}{dp} \ldots \frac{dy}{d\lambda}$	парциальные чувствительности	partial sensitivity
	$S_x = S_{x_0} + \frac{dy}{dT}\Delta T + \frac{dy}{dT^2}\Delta T$ or $S_x = S_{x_0} e^{-K_1 T}$ or $S_x = S_{x_0} + S'_{x_0} e^{-K_1 T}$	изменение чувствительности в зависимости от времени работы	variation in sensitivity, function of oper. time

/36

Table 1, Part 1 (Continued)

I	2	3	4
8	V	объем	volume
	G	вес	weight
	$\frac{V}{y_n}$	относительное значение объема - "удельный объем"	specific volume
	$\frac{G}{y_n}$	относительное значение веса - "удельный вес".	specific weight
	2. Dynamic properties and characteristics		
I	$\frac{y}{x} = \frac{b_0 p^m + b_1 p^{m-1} + \dots + b_m}{a_0 p^n + a_1 p^{n-1} + \dots + a_n}$	переходная функция	transient function
	$\frac{y}{x} = \frac{e^{-kP_t}}{a_0 p^n + a_1 p^{n-1} + \dots + a_n}$	временная характеристика с учетом времени запаздывания.	time charact. with delay time
	$G(\omega) = \frac{\dot{y}_m}{\dot{X}_m} = \frac{1}{a_0 (j\omega)^n + a_1 (j\omega)^{n-1} + \dots + a_n}$	амплитудно-фазовая характеристика	amplitude-phase charact.
	$\lvert G(\omega)\rvert = \left\lvert\frac{\dot{y}_m}{\dot{X}_m}\right\rvert = \frac{1}{\sqrt{A^2(\omega)+B^2(\omega)}}$	амплитудно-частотная характеристика	amplitude-frequency charact.
	$\varphi = \operatorname{arctg} \frac{B(\omega)}{A(\omega)}$	фазо-частотная характеристика	phase-frequency charact.
	$\frac{G(\omega)}{G(0)} = \Psi_c(\omega)$	логарифмическая амплитудно-частотная характеристика.	log. amplitude-frequency charact.
2	$S_i = \frac{y_2' - y_1'}{x_2 - x_1} = \frac{\Delta\left(\frac{dy}{dt}\right)}{\Delta x}$	чувствительность элемента с интегральной зависимостью	sensitivity of integrating element
	$S_d = \frac{y_2 - y_1}{x_2' - x_1'} = \frac{\Delta y}{\Delta\left(\frac{dx}{dt}\right)}$	чувствительность элемента с дифференциальной зависимостью	sensitivity of differentiating element
	$y(t) = S\left[x(t) + \frac{1}{T_n}\int_0^t x(t)\,dt\right]$	уравнение элемента с PI-звеньями	equation of element with PI sections
	$\frac{y}{X} = \pm \frac{1/j\omega}{\delta I/j\omega + 1} p$		
	$y(t) = S\left[x(t) + T_D \frac{dx(t)}{dt}\right]$	уравнение элемента с РД-звеньями	equation of element with PD sections
	$\frac{y}{X} = \pm p \frac{1 + j\omega T_D}{1 + j\omega T_d}$		
	$y(t) = S\left[x(t) + \frac{1}{T_n}\int_0^t x(t)\,dt + T_D \frac{dx(t)}{dt}\right]$	уравнение элемента с PIД-звеньями	equation of element with PID sections
	$\frac{y}{X} = \pm p \frac{\frac{1}{j\omega} + 1 + T_D \cdot s}{\frac{\delta I}{j\omega} + 1 + T_d \cdot s}$		

Table 1, Part 1 (Continued)

I	2	3	4
		3. Error	
I	$\Delta y = f_0(x) - f_{0T}(x)$	методическая погрешность	methodical error
2	$\Delta y_2 = \left[f(\bar{x}) - \bar{S}_0(x - x_0)\right]_{max}$	погрешность от нелинейности	error due to nonlinearity
3	$\Delta y_i = \frac{1}{2}\left\lvert\frac{\sum_1^n y'_x}{n} - \frac{\sum_1^n y''_x}{n}\right\rvert_{max} = \lvert S_0 \cdot \Delta x_x\rvert_{max}$	погрешность от гистерезиса и сухого трения	error due to hysteresis and backlash
4	$\frac{\Delta y_i}{y_{max}}$	относительная погрешность от гистерезиса	relative error due to hysteresis
5	$\Delta y_3 = \left[\frac{\Delta S_0}{\Delta t} \cdot x_0 \cdot t_0\right]_{max}$	дрейф	drift
6	$\Delta y_\varphi = \left[S_\theta \cdot \Delta\theta^\circ + S_z \cdot \Delta z + \dots + S'_\alpha \cdot \Delta\alpha\right]$	абсолютная дополнительная инструментальная погрешность	absolute complementary instrument error
7	$\frac{\Delta y_\varphi}{y_{max}}$	относительная дополнительная инструментальная погрешность	relative complementary instrument error
		повторяемость (измерение выходных сигналов)	reproducibility
	$(\Delta y_\Sigma = \Sigma \bar{y}_i + n\sigma_\Sigma)$	разброс	spread
8	$\Delta y_\Sigma = \Sigma y_i$	абсолютная погрешность	absolute error
	$\frac{y_{\Sigma i}}{y_i}$	относительная погрешность	relative error
	$\frac{\Delta y_{\Sigma i}}{y_{max}}$	приведенная погрешность	reduced error
		Dynamic errors	
I	$\Delta y_t = y_t - y_k$	динамическая погрешность	dynamic error
		4. Information characteristics	
I	$F = \Delta f \lg_2\left[1 + \frac{x_{max} - x_{min}}{\Delta x_\Sigma}\right]$	"сечение потока информации"	information flow
2	$A = \Delta f T_c \lg_2\left[1 + \frac{x_{max} - x_{min}}{\Delta x_\Sigma}\right]$	количество (объем) информации	volume of information
3	$M = S'_x \Delta f \lg_2\left[1 + \frac{x_{max} - x_{min}}{\Delta x_\Sigma}\right]$	сводный параметр	cumulative parameter

Table 1, Part 1 (Continued)

I	2	3	4
		5. Reliability	
I	R_ω	надежность по отношению к полным отказам	reliability, total failure
2	R_b	надежность по отношению к неполным отказам	reliability, partial failure
3	$R_a = e^{-\int_0^t \lambda dt}$	надежность	reliability
4	λ	интенсивность отказов	failure rate
	λ_o	интенсивность отказов при номинальном режиме	failure rate, nominal operation
5	$R = R_a \cdot R_b$	результирующая надежность....	resultant reliability
6	T_T	технический ресурс	technical resource
	T_c	срок службы	useful life
7	K_T	коэффициент технической готовности	technical readiness factor
	$U = \frac{T_m - T_T}{T_m}$	коэффициент использования ...	utilization factor
8	$T_m = \frac{1}{\lambda}$	среднее время до первого отказа	av. time to first failure
	T_z	среднее время ремонта	av. repair time

TABLE 1. PART 2. BASIC CHARACTERISTICS AND PARAMETERS FOR SWITCHING ELEMENTS. /39

№ п/п	Designation	Terms	
I	2	3	4
		1. Static parameters and characteristics	
I	x_a	параметры срабатывания	operate parameters
2	$x_{\text{в}}$	параметры возврата	reset parameters
3	$K_{\text{в}} = \frac{x_{\text{в}}}{x_a}$	коэффициент возврата	reset factor
4	x_p	рабочий параметр	operating parameter
5	$\frac{x_p}{x_a} = K_p$	коэффициент запаса при срабатывании.	operate safety factor
	$\frac{x_{\text{в}}}{x_p} = K_p'$	коэффициент запаса при отпускании	reset safety factor
6	$K_y = \frac{y_{max}}{x_a}$	коэффициент управления ...	control factor
	$K_K = \frac{y_{max}}{y_{min}}$	кратность управления	control multiplicity factor
		2. Dynamic characteristics	
I	t_a	время срабатывания	operate time
	$t_{\text{в}}$	время возврата (отпускания)	reset time
	$t_a = f_1(K_p)$; $t_{\text{в}} = f_2(K_p') = f_2'(K_p)$	временные характеристики релейного элемента	time characteristics, switching element
2	$\left.\begin{matrix} t_a = f_{1a}(K_p; z) \\ t_{\text{в}} = f_{2a}(K_p; t) \end{matrix}\right\}$	временные характеристики настраиваемых элементов	time characteristics, adjustable elements
		Reliability	
I	$R_{\text{в}}' = \frac{1}{\sqrt{2\pi}\sigma_a}\int_{-\infty}^{x_p} e^{-\frac{(x-\bar{x}_a)^2}{2\sigma_a^2}}dx$	надежность срабатывания	operate reliability
2	$R_{\text{в}}'' = 1-\frac{1}{\sqrt{2\pi}\sigma_{\text{в}}}\int_{-\infty}^{x_p} e^{-\frac{(x-\bar{x}_{\text{в}})^2}{2\sigma_{\text{в}}^2}}dx$	надежность отпускания	reset reliability

Table 1, Part 2 (Continued)

I	2	3	4
3	$R_{\delta} = R_{\delta}' \cdot R_{\delta}''$	надежность работы (надежность срабатывания и отпускания) ...	operating reliability (operate and reset reliability)
4	$R_{в} = e^{-\lambda t}$	надежность в отношении отсутствия внезапных отказов	reliability and sudden failures
		Performance data	
I	C_x	стоимость с учетом транспортных расходов и стоимость монтажа и наладка элемента	cost, (transportation, installation and adjustment)
	n	число одинаковых элементов в функциональной схеме	No. of identical elements in functional system
	T	срок службы технологического оборудования	life of technological installation
2	C_{y_x}	стоимость энергии и вспомогательных материалов на час работы элементов	energy cost and cost of auxiliary materials per hour of operation
	$C_2 = \sum_{x=1}^{x=m} C_{y_x} \cdot n_x \cdot T$	затраты на вспомогательную энергию и вспомогательные материалы	cost of additional energy and additional materials
3	$N = \sum_{1}^{m} n_x$	общее число элементов	total No. of elements
	N_0	число элементов, приходящихся на одного человека из обслуживающего персонала	No. of elements per serviceman
	C_t	стоимость человеко-часа	cost per man-hour
	$C_3 = \frac{N}{N_0} \cdot C_t \cdot T$	затраты на эксплуатационное обслуживание	cost of operating expense
4	$C_y = \sum_{x=1}^{x=m} n_x \cdot C_0 \cdot q_x$, $q_x = \lambda T$	возможная стоимость потерь в технологическом процессе	possible cost due to losses in technological process
5	$C_{\Sigma} = \sum_{1}^{5} C_k$	суммарные затраты	total costs

TABLE 2

Equations and characteristics	UNIT: Amplification (P)	Aperiodic	Oscillatory	Integrating (I)	Differentiating (D)	Differentiating, first order (ideal)	Differentiating, second order (ideal)	PI	PD	PID	With delay
Differential equation	$y = kx$ $(k = S_0)$	$T\frac{dy}{dt} \pm y = kx.$	$T^2\frac{d^2y}{dt^2} \pm 2D\frac{dy}{dt} + y = kx$	$y = \frac{1}{T_I}\int_0^t x\,dt$ или $\frac{dy}{dt} = k_I x$, $k_I = \frac{1}{T_I}$	$y = k_D \cdot \frac{dx}{dt}$	$y = k(T_{D1}\frac{dx}{dt} + x)$	$y = k(T_{D2}^2\frac{d^2x}{dt^2} + T_{D1}\frac{dx}{dt} + x)$ $(T_{D1} = 2\zeta T_{D2})$	$y = k[x + \frac{1}{T_I}\int_0^t x\,dt]$	$y = k[x + T_D\frac{dx}{dt}]$	$y = k[x \cdot a_0 + \frac{1}{T_I}\int_0^t x\,dt + T_D\frac{dx}{dt}]$ $a_0 = 1 + \frac{T_D}{T_I}$	$y(t) = k \cdot x(t - T_\tau)$
Differential equation in operational form	—	$[Tp \pm 1]y = kx$	$[T^2p^2 \pm 2Dp + 1]y = kx$	$p\,y = k_I x$ или $y = \frac{k_I}{p}x$	$y = k_D\,p\,x$	$y = k[T_{D1}p + 1]x$	$y = k(T_{D2}^2p^2 + T_{D1}p + 1)x$	$y = k(1 + \frac{1}{pT_I})x$	$y = k[1 + T_D p]x$	$y = k[a_0 + \frac{1}{T_I p} + T_D p]x$	$W(p) = k e^{-p \cdot T_\tau}$
Transfer function	$W(s) = k$	$W(s) = \frac{k}{Ts \pm 1}$	$W(s) = \frac{k}{T^2s^2 \pm 2Ds + 1}$	$W(s) = \frac{k_I}{s}$	$W(s) = k_D s$	$W(s) = k(T_{D1}s + 1)$	$W(s) = k(T_{D2}^2s^2 + T_{D1}s + 1)$	$W(s) = k[1 + \frac{1}{sT_I}]$	$W(s) = k[1 + T_D s]$	$W(s) = k[a_0 + \frac{1}{T_I s} + T_D s]$	$W(s) = k \cdot e^{-T_\tau s}$
Amplitude-phase characteristic	$W(j\omega) = k$	$W(j\omega) = \frac{k}{Tj\omega \pm 1}$	$W(j\omega) = \frac{k}{1 + 2Dj\omega + T^2(j\omega)^2}$	$W(j\omega) = \frac{k_I}{j\omega}$	$W(j\omega) = k_D j\omega$	$W(j\omega) = k(1 + T_{D1}j\omega)$	$W(j\omega) = k[(j\omega)^2T_{D2}^2 + T_{D1}(j\omega) + 1]$	$W(j\omega) = k[1 + \frac{1}{j\omega T_I}]$	$W(j\omega) = k[1 + j\omega T_D]$	$W(j\omega) = k[a_0 + \frac{1}{j\omega T_I} + j\omega T_D]$	$W(j\omega) = k \cdot e^{-T_\tau j\omega}$
Amplitude-frequency characteristic	$A(\omega) = k$; $\log A(\omega)$, $\log k$, $\log\omega$	$A(\omega) = \frac{k}{\sqrt{(T\omega)^2 + 1}}$; $\log A(\omega)$, $\omega_0 = 1/T$, $\log\omega_0$, $\log\omega$	$A(\omega) = \frac{k}{\sqrt{(1 - T^2\omega^2)^2 + 4D^2\omega^2}}$; $\log A(\omega)$, $\log 1/T$, $\log\omega$	$A(\omega) = \frac{k_I}{\omega}$; $\log A(\omega)$, $\log k_I$, $\log\omega$	$A(\omega) = k_D\omega$; $\log A(\omega)$, $\log k_D$, $\log\omega$	$A(\omega) = k\sqrt{1 + (\omega T_{D1})^2}$; $\log A(\omega)$, $\log 1/T_{D1}$, $\log\omega$	$A(\omega) = k\sqrt{(1 - T_{D2}^2\omega^2)^2 + T_{D1}^2\omega^2}$; $\log A(\omega)$, $\log\frac{1}{T_{D1}}$, $\log 1/T_{D2}$, $\log\omega$	$\log A(\omega)$, $\log\omega$	$\log A(\omega)$, $\log\omega$	$\log A(\omega)$, $\log\omega$	$\log A(\omega)$, $\log k$, φ, $\log\omega$
Phase-frequency characteristic	0	$\varphi(\omega) = -\mathrm{arctg}(\omega T)$	$\varphi(\omega) = \mathrm{arctg}\frac{2D}{1 - T^2\omega^2}$	$\varphi(\omega) = -\frac{\pi}{2}$	$\varphi(\omega) = \frac{\pi}{2}$	$\varphi(\omega) = \mathrm{arctg}(\omega T_{D1})$	$\varphi(\omega) = \mathrm{arctg}\frac{\omega T_{D1}}{1 - T_{D2}^2\omega^2}$	$-90°$, $\log\omega$	$+90°$, $\log\omega$	$+90°$, $-90°$, $\log\omega$	—
Transient function	$h(t) = k$	$h(t) = k(1 - e^{-\frac{t}{T}})$	$h(t) = k[1 - \frac{e^{-\frac{\zeta}{T}t}}{\sqrt{1 - \zeta^2}}\sin(\omega t + \varphi)]$ $\zeta = \frac{D}{T}$	$h(t) = k_I t$	$h(t) =$	$h(t) = k\{[1] + T_{D1}\delta(t)\}$ $\delta(t)$ delta function	$h(t) = k\{[1] + T_{D1}\delta(t) + T_{D2}^2\frac{d\delta(t)}{dt}\}$	PI	PD	PID, I, P, D	$h(t) = k$ при $t \geq T_\tau$
Adjust. param.	k			k_I				k, T_I	k, T_D	k, T_I, T_D	T_τ
Symbolic designation								PI	PD	PID	